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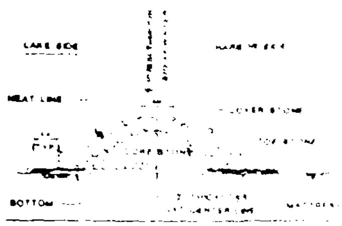

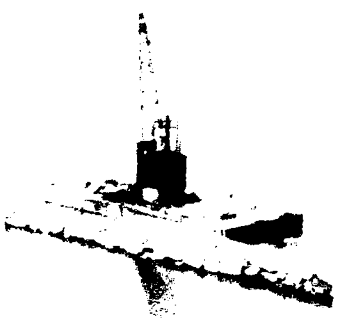

REMR RESEARCH PROGRAM

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CO-10

STUDY OF BREAKWATERS CONSTRUCTED WITH ONE LAYER OF ARMOR STONE DETROIT DISTRICT

by

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US Army Engineer District, Detroit
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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

Destroy this report when no longer needed. Do not return it to the originator.

COVER PHOTOS

TOP — Typical cross section of rubble-mound breakwater with one-layer armor stone

MIDDLE — Harrisville Harbor breakwater constructed with armor stone of Michigan limestone quarried by drilling and blasting

BOTTOM — Crane barge placing armor stone on rubble-mound breakwater

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This study was carried out to provide documentation of the design, construction, repair, rehabilitation, maintenance, environmental loading, and economic history of one-layer armor-stone breakwaters in the US Army Engineer District, Detroit, and to present cost comparisons for one-layer stone breakwaters versus two-layer stone breakwaters.

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PREFACE

This report was prepared as part of the coastal problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was carried out under REMR Work Unit No. 32327, "Repair of Localized Damage to Rubble-Mound Structures." The REMR program is under the general direction of Mr. James E. Crews and Dr. Tony C. Liu, REMR Overview Committee (REMROC), Headquarters, US Army Corps of Engineers (HQUSACE); Mr. Jesse A. Pfeiffer, Jr., Directorate of Research and Development, HQUSACE; members of the REMR Field Review Group; Mr. John H. Lockhart, REMR Problem Area Monitor, HQUSACE; Mr. William F. McCleese, REMR Program Manager, US Army Engineer Waterways Experiment Station (WES); and Mr. D. D. Davidson, REMR Coastal Problem Area Leader, Coastal Engineering Research Center (CERC), WES.

This work was carried out as a joint effort of WES and the US Army Engineer District, Detroit. The portion of the work conducted at WES through CERC during the period from October 1985 through September 1986 was under the general direction of Dr. R. W. Whalin, former Chief, Mr. C. C. Calhoun, Jr., former Acting Chief, Dr. J. R. Houston, present Chief of CERC, Mr. C. E. Chatham, Jr., Chief, Wave Dynamics Division, and Mr. D. D. Davidson, Chief, Wave Research Branch. The portion of the work conducted at the Detroit District was under the general direction of Mr. B. Malamud, Acting Chief, Engineering Division, Mr. P. Mills, Chief, Great Lakes Hydraulics and Hydrology Branch, and Mr. T. C. Nuttle, Chief, Coastal Section. This report was prepared by Mr. J. R. Wolf, Hydraulic Engineer, Detroit District. This report was edited by Mrs. N. Johnson, Information Products Division, WES, under the Interpersonnel Agreement Act.

The case histories were written from information obtained from annual structure inspection reports, conferences, telephone conversations, project plans and specifications, project files and correspondence, design memorandums, literature reviews, model studies, surveys, and photographs.

Acting Commander and Director of WES during preparation of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres
pounds per cubic foot	16.01846	kilograms per cubic metre
pounds (mass)	0.4535924	kilograms
tons	907.1847	kilograms

STUDY OF BREAKWATERS CONSTRUCTED WITH ONE LAYER OF ARMOR STONE; DETROIT DISTRICT

PART I: INTRODUCTION

Background

1. The US Army Engineer District (USAED), Detroit, has 16 breakwaters (Plate 1) within the District, all or part of which were designed and constructed with one layer of armor-stone protection. (This type of construction was used between 1918 and 1975.) This study was carried out to document the design, construction, repair, rehabilitation, maintenance, environmental loading, and economic history for these structures. Five of the sixteen harbors were selected for cost studies to compare cost to construct the breakwater today using a one-layer design (as it was constructed) with cost using a two-layer design. Maintenance costs for the 16 breakwaters with one layer of armor stone also were compared with maintenance costs for typical breakwaters constructed with two layers of armor stone. Currently, two layers of armor stone are recommended in the Shore Protection Manual (US Army Engineer Waterways Experiment Station (USAEWES) 1984). The USAED, Detroit, has eight breakwaters within the District, all or part of which are of the two-layer design.

2. The typical one-layer design used in the USAED, Detroit, was constructed with a layer of specially placed armor stones. The armor stones were placed over a core of smaller stones usually on a mattress of stone from 1 to 2 ft* thick placed on the lake bed. The crest width was a minimum of 8 ft. The side slopes were usually 1.75H:1V on the lake side and 1.5H:1V on the harbor side of the breakwater. Some breakwaters had side slopes of 1.5:1V on both sides. The typical cross section is shown in Plate 2, and pertinent summary information on each breakwater is presented in Table 1 and Appendix A.

3. The typical two-layer armor-stone breakwater design which was used for calculations in this report has two layers of armor stone, crest width,

* A table of factors for converting non-SI (metric) units of measurement is presented on page 3.

armor layer and underlayer thickness as recommended in the Shore Protection Manual (USAEWES 1984) and calculated using the Coastal Engineering Research Center's (CERC), USAEWES, MACE computer program HUDSON. The underlayer stone weight is one-tenth the weight of the armor stone, and the side slopes are 2H:1V and 1.5H:1V. The typical cross section is shown in Plate 2.

Purpose

4. The purpose of this report is to document as much history and field experience as possible on the construction, repair, and maintenance of one-layer armor-stone breakwaters within the USAED, Detroit. Selected breakwaters are used to discuss original design, constructibility of one-layer breakwaters, and cost comparison with two-layer armor-stone structures.

PART II: DESIGN OF ONE-LAYER ARMOR-STONE BREAKWATERS

5. Design calculations are not available for most of the breakwaters studied in this report. Hudson's formula, which is still in use, was used for one of the later designs. The value for the stability coefficient (KD) is 3.5 for Leland Harbor breakwater (USAED, Detroit, 1965). The values estimated for Caseville (USAED, Detroit, 1959) and Harrisville (Brater and Stair 1951) are 1.2 and 2.3, respectively. These values are probably smaller because the stone is blasted rock, which is angular and less stable than the Bedford Limestone on the Leland Harbor breakwater. The values of KD for Little Lake Harbor and Marquette Harbor are 4.7 and 7.0, respectively, estimated from the existing stone sizes and the currently estimated wave heights. The estimated KD's are listed in Table 2.

6. The armor stones should be shaped and selected so that they will fit into the breakwater with openings between the individual stones that are small enough to retain core stones 50 lb and larger. Cut stone is the best shape and the most stable; however, blasted stone has proven satisfactory in some breakwaters. This cut stone is quarried into blocks by drilling holes in straight lines at the sides and ends of each block. Then the rock is split along the lines of holes and at the bottom along a seam at the bedding plane. The holes are relatively small and drilled only partially through the layer of rock which is being quarried. Similar procedures are used to quarry both limestone and hard rock.

7. The following specifications are for core stone used in the later one-layer breakwater designs. Core stone shall consist of a well-graded mixture of sizes that will form a compact mass in place. The mixture will consist principally of pieces weighing 50 lb and more. Approximately 50 percent by weight will be in pieces weighing 0.5 to 1 or more tons. Not more than 12 percent will be in pieces weighing less than 50 lb each, and not more than 3 percent will consist of stones weighing less than 1 lb. Where space available in the proposed work does not permit the inclusion of the larger size stones, these sizes shall be omitted from the mixture. The larger size stones shall be compact in shape. Individual stones shall have an average thickness of not less than 25 percent of the average width. Core height of one-layer armor structures is usually higher than two-layer armor structures with the same crown elevation, thus wave transmission through the structure is reduced

but wave runup and overtopping is increased.

8. The following specifications are for mattress stone used in the later c· ayer breakwater designs. Mattress stone will consist of a reasonably we..-graded mixture of sizes that will form a compact mass in place. The stone will be quarry run of 300-lb maximum size. The mixture shall not contain more than 3-percent fines and approximately 50 percent of the pieces shall weigh between 100 and 300 lb. For this section of the specifications, fines are defined as that part of the stone smaller than 3/8 in. in size. This mattress stone is coarser than the mattress stone used today, which is usually 1 to 50 lb, and the stone is more resistant to possible leaching of foundation material.

PART III: COST COMPARISON OF FIVE BREAKWATERS DESIGNED WITH ONE AND TWO LAYERS OF ARMOR STONE

9. Five harbors were selected for a comparison of the estimated cost to construct the breakwaters with one layer of armor stone and similar size breakwaters with two layers of armor stone. The five harbors selected for the comparison were Caseville Harbor, Harrisville Harbor, Leland Harbor, Little Lake Harbor, and Marquette Harbor (Figures A1-A5).

10. For the breakwaters designed with one layer of armor stone, the wave heights listed in Table 3 are from records. Thickness of the armor layers was taken as one stone diameter. The armor-stone weights shown in Table 3 were taken from the project maps. For the breakwater designs with two layers of armor stone, the wave heights listed in Table 4 were calculated using the TMA method (Hughes 1984) of estimating depth-limited irregular wave heights. The computer program HUDSON was used to estimate the armor-stone weight W, the crest width B, and the armor-layer thickness r. These values are listed in Table 4. The typical cross section is shown in Plate 2.

11. The material quantities for the one-layer structures (Table 5) were estimated using breakwater cross sections from the project maps, and cross sections with 2H:1V and 1.5H:1V side slopes were used for the two-layer design (Table 6). The lengths of the breakwaters were taken from the project maps for both designs. The water depths were taken from National Oceanic Atmospheric Administration charts for both designs.

12. The stone costs listed in Tables 7 and 8 are current estimated costs. It was thought that current prices would be best for comparison purposes. Actual costs vary according to location due to transportation costs. The estimated cost for stone in 1960 was about one-half the current estimated cost.

13. The one-layer armor-stone breakwater usually requires less armor stone than a two-layer armor-stone design. However, the one-layer design requires more core stone if the volume is the same. The cost saving, if any, is due to the difference in cost between the core stone and the armor stone. Two-layer breakwater designs with both 2H:1V and 1.5H:1V slopes have been included in this study. The crest width was calculated for the two-layer designs and was taken from the project maps for the one-layer designs. The void ratios were also different (37 percent for the two-layer designs; 25 percent

for the armor stone and 30 percent for the core stone for the one-layer designs).

14. The USAED, Detroit, was able to construct the breakwaters in Lake Michigan from the Bedford Limestone because the stone was available from quarries at low cost due to defects such as poor color; these defects caused the stone to be rejected for building purposes. Stone is plentiful in the Great Lakes area: cut limestone is available from quarries in Wisconsin at the present time, and limestone quarried by blasting is available in Michigan.

15. The cost comparison study compared the one-layer armor-stone breakwaters as they were constructed with two-layer armor-stone designs with 1.5H:1V and 2H:1V side slopes as they would be constructed now. The quantities estimated were multiplied by the present estimated cost per ton. The resulting total estimated costs for stone are listed in Table 9.

16. The total estimated weight of stone, weight of stone per foot, and cost per foot for a breakwater with one layer of armor stone are listed in Table 10. The same quantities are listed for two-layer breakwaters with 2H:1V and 1:5H:1V slopes in Table 11.

PART IV: CONSTRUCTIBILITY OF BREAKWATERS WITH ONE LAYER OF ARMOR STONE

17. The breakwater designed with one layer of armor stone is constructed by specially placing armor stones on a bed of core stone. The breakwater may be constructed by floating plant or by land-based construction equipment. The armor stones are set in place by means of a crane equipped with a chain sling and hooks or a grapple. Each armor stone is selected from the supply and set in place. Placement is checked by sight above water or by feeling with pikes (wooden poles) when placing armor stone under water. When the block is in place, it is released. Divers are required in water deeper than 25 ft.

18. There are a number of different types of stones used for armor stone. The breakwaters at Leland Harbor and New Buffalo Harbor were constructed with armor stone of Bedford Limestone from southern Indiana. Bedford Limestone is principally quarried for building stone. It is split or cut into blocks at the quarry by a machine mounted on rails that drills holes into the stone in straight lines along the sides and ends of the blocks. The stone is then split into blocks through the lines of holes. The stone blocks are square cornered and appear to be very stable. This armor stone is reasonably priced because it is made from stock with a poor quality color and therefore was rejected for building stone. Harrisville Harbor breakwater in Lake Huron was constructed with limestone armor stone which was quarried by blasting and sorted to meet the size requirements. Armor stones at Marquette are hard rock that appear to be boulders. These stones are rounded more on the corners and smoother than the armor stones on the other breakwaters. Presque Isle Harbor breakwater is protected by armor stones split from hard rock at the quarry by a mechanical process using a line of holes drilled along the sides and ends of the blocks. The stone is then broken through the line of holes using hydraulically driven wedges. All of these processes produce armor stone that is satisfactory for construction of breakwaters with one layer of armor stone.

19. The cover stone included toe stone and was usually specified by a minimum weight in tons. The toe stone was select heavier armor stones. The tolerance for placing cover stone was 12 to 18 in. above the neat line to 6 in. below the neat line, depending on the size of the stone.

20. Failure of the breakwaters with one layer of armor stone could result from placing armor stones too far apart or by using core stone that contains too many fines (either or which may allow some of the core stone to escape from the breakwater through the openings between the armor stones). Segregation of fine material, such as can result from end dumping, should also be avoided. They also may fail because of scour or armor stones that are too light, as can any armor-stone-protected breakwater.

21. The core stone made from local quarries was placed on mattress stone, (usually in a layer from 1 to 2 ft thick) extending past the toe of the armor stone. The core was graded to the shape of the final breakwater before placing the armor stone.

22. Experienced construction personnel state that special placement of the armor stone did not take significantly longer than random placement. There are also fewer armor stones to handle and place.

23. A breakwater constructed with one layer of armor stone should be as constructible now with modern day equipment as it was in the past. This type of breakwater has been constructed successfully with four different types of armor stone. Similar amounts of skill and care are required in placing the armor stone as on a two-layer design.

24. Table 12 lists the sizes and quantities of stone used in repair of the breakwaters as shown in the USAED, Detroit, records. The smaller stone is used to build up areas as required to level and support the replaced armor stone.

25. Figures 1 through 9 show breakwater construction, armor-stone quarrying, and breakwater structures. Figures 1 through 3 show armor stone being placed on a breakwater and being cut in the quarry. Figures 4 through 9 show six breakwaters in the Great Lakes which have one layer of armor stone.

26. The one-layer armor-stone breakwaters have less reserve stability than a two-layer design. Once the armor stone has been displaced, the core stone is exposed to attack by storm waves. However, there has been only a relatively small amount of repair required on the one-layer armor-stone breakwaters.

27. The breakwaters in the USAED, Detroit, are inspected in the spring after the spring thaw by aerial reconnaissance. These inspections are followed by surface inspections and later by detailed annual inspections.

28. Damages such as displaced armor stone found during the inspections

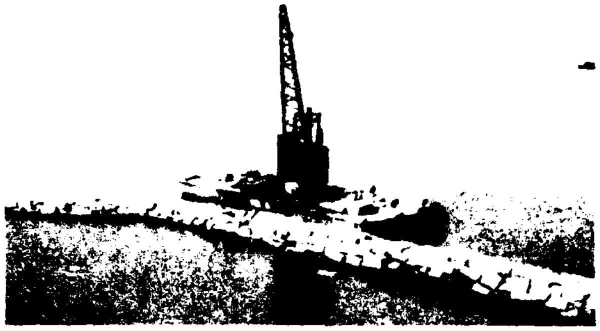

Figure 1. Crane barge placing armor stone on rubble-mound breakwater

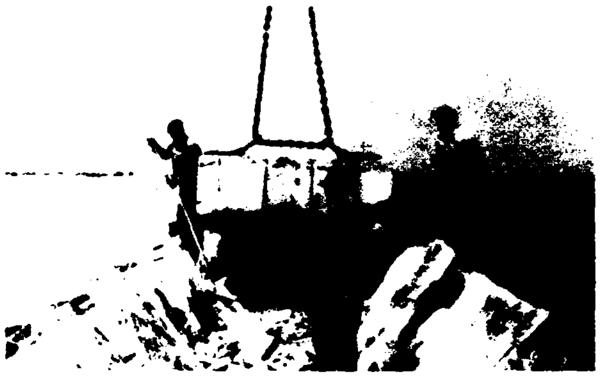

Figure 2. Block of cut armor stone being placed on the crest of rubble-mound breakwater using a chain sling and hooks

Figure 3. Pneumatic stone-cutting machine cutting armor stone in quarry

Figure 4. Marquette Harbor breakwater constructed with one layer of armor stone of hard rock

Figure 5. Presque Isle Harbor breakwater covered with one layer of armor stone of hard rock quarried by drilling and splitting

Figure 6. New Buffalo Harbor breakwater constructed with one layer of Bedford Limestone armor stone

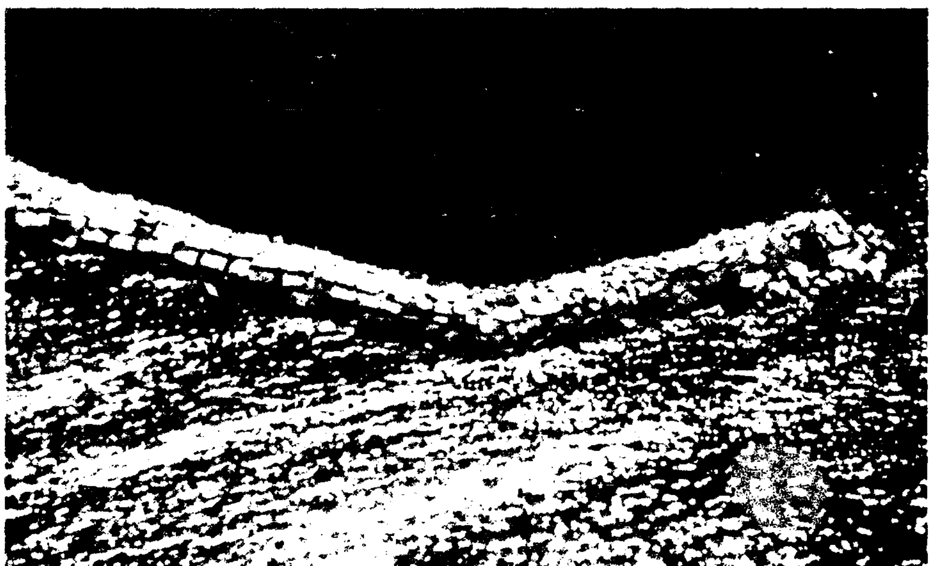

Figure 7. Leland Harbor breakwater constructed with one layer of Bedford Limestone armor stone

Figure 8. Harrisville Harbor breakwater constructed with armor stone of Michigan limestone quarried by drilling and blasting

Figure 9. Muskegon Harbor breakwater constructed with armor stone of Michigan limestone quarried by drilling and blasting

are repaired as soon as possible. More severe damage would, of course, have priority.

29. To expedite the work, repairs to the breakwaters are usually made by advance open-end contracts.

30. Repairs are made during the spring and summer construction season. Most damages occur during the fall storm season. The ice cover during the winter is usually beneficial, because it reduces storm wave action.

31. In general, given the same overall structure elevation, the core of the one-layer armor-stone structures is usually higher than those with two-layer armor stone, thus the higher core and tighter armor placement (lower porosity) of the one-layer system reduces wave transmission through the structure but increases wave runup and overtopping. Historical design records and prototype performance data were not available to adequately compare the relative merits of these factors on one- and two-layer structures.

PART V: CONCLUSIONS

32. Stability coefficients, KD , for one-layer armor-stone breakwaters in this study varied considerably. The KD value from Leland Harbor (USAED, Detroit, 1965) of 3.5 for Bedford Limestone appears to be reasonable for design with cut armor stone. The KD value of 2.3 for blasted armor stone from Harrisville Harbor also seems reasonable (Brater and Stair 1951).

33. Materials and skills needed to construct the one-layer armor-stone breakwater should be available at the present time. Cut stone blocks are available as well as blasted quarry stones. Crane operators, who can place the stone with the required precision, should be available.

34. The monitoring and inspection provided by the Detroit District for the one-layer design is the same as that for the two-layer design.

35. Of the 16 breakwaters constructed with the one layer of armor stone included in this study, 12 have required minor repairs. Table 12 indicates quantities of repair stone found in Detroit District records.

36. It is impossible to compare the repairs and maintenance costs directly between the one- and two-layer armor-stone breakwaters, because each is an individual case. It can be concluded that generally both types of breakwaters required relatively low maintenance.

37. The information collected for this study indicated that a one-layer design breakwater can perform satisfactorily when properly designed and constructed. The one-layer design must not contain fine material that can work out of the core. Armor stone must be heavy enough to prevent displacement and loss of core stone. Each armor stone in a one-layer breakwater must be set in close contact with the adjacent stones ensuring support and structural integrity. The maximum estimated cost savings based on initial construction of breakwater designs with one layer of armor stone compared to the breakwater designs with two layers of armor stone is from 21 to 32 percent with a 2H:1V slope and from -8 to 20 percent with a 1.5H:1V slope for the five examples considered and shown in Table 9. Three of the five examples are between -2 and 4 percent with the two-layer design breakwater constructed with a 1.5H:1V slope. This is not a significant difference.

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Table 1

Summary of Breakwater

Location	Table	Figure	Length, ft	Date of Origin	Repaired
Caseville Harbor, MI*	A1	A1	1,780	1962	No
Harrisville Harbor, MI*	A2	A2	2,659	1959	Yes
Leland Harbor, MI*	A3	A3	1,200	1968	Yes
Little Lake Harbor, MI*	A4	A4	922	1964	Yes
Marquette Harbor, MI*	A5	A5	1,500	1918	Yes
Alpena Harbor, MI	A6	A6	700	1939	No
Cheboygan Harbor, MI	A7	A7	775	1969	Yes
Clinton River, MI	A8	A8	1,150	1966	No
Hammond Bay Harbor, MI	A9	A9	1,905	1965	Yes
Mackinaw City Harbor, MI	A10	A10	430	1965	Yes
Manistique Harbor, MI	A11	A11	572	1953-1963	No
Muskegon Harbor, MI	A12	A12	3,064	1930	Yes
New Buffalo Harbor, MI	A13	A13	1,870	1975	Yes
Pentwater Harbor, MI	A14	A14	60	1959	Yes
Presque Isle Harbor, MI	A15	A15	1,600	1938	Yes
Two Harbors, MN	A16	A16	326	1948	Yes

* Selected for cost studies to compare construction costs for breakwater with one-layer design to two-layer design.

Table 2

Estimated Stability Coefficients (KD) for Armor Units

Harbor	KD
Caseville	1.2
Harrisville	2.3
Leland	3.5
Little Lake	4.7
Marquette	7.0

Table 3

Characteristics of One-Layer Armor-Stone Breakwater

Harbor	Armor Unit Weight, w_r, pcf	Design Wave Height, H, ft
Caseville	162.0	6.0
Leland	149.8	11.0-8.6
Harrisville	162.0	10.0-4.5
Little Lake	162.0	Unknown
Marquette	173.0	Unknown

Harbor	Structure Slope, cot θ	Minimum Armor Weight W, ton	Crest Width B, ft	Armor Thickness r, ft
Caseville	1.75 front 1.50 back	1, 2	8	2.6, 3.3
Leland	1.75 front 1.50 back	5	8	4.5
Harrisville	1.75 front 1.50 back	5, 3	8	4.5, 3.8
Little Lake	1.75 front 1.50 back	5, 3	8	4.5, 3.8
Marquette	1.75 front 1.75 back	10	17	5.7

Table 4

Characteristics of Two-Layer Armor-Stone Breakwater

Harbor	Armor Unit Weight, w_r, pcf	Design Wave Height, H, ft
Caseville	162.0	11.0
Leland	167.0	9.7
Harrisville	162.0	12.4
Little Lake	162.0	12.7
Marquette	173.0	19.9

Harbor	Structure Slope, cot θ	Armor Weight W, ton	Crest Width B, ft*	Armor Thickness r, ft
Caseville	2.0	3.3	10.3	6.9
Leland	2.0	2.0	8.7	5.8
Harrisville	2.0	4.8	11.7	7.8
Little Lake	2.0	5.1	11.9	8.0
Marquette	2.0	15.3	16.8	11.2
Caseville	1.5	4.4	11.4	7.6
Leland	1.5	2.7	9.6	6.4
Harrisville	1.5	6.3	12.8	8.5
Little Lake	1.5	6.8	13.1	8.8
Marquette	1.5	20.4	18.5	12.4

* The crest width is based on three armor-stone widths.

Table 5

Estimated Quantities of Stone for Breakwaters

With One Layer of Armor Stone

Harbor	Armor Stone tons	Core Stone tons	Mattress Stone tons
Caseville	12,200	7,900	9,100
Harrisville	27,400	21,400	16,500
Leland	18,500	17,800	8,100
Little Lake	7,900	4,400	4,900
Marquette	99,500	277,400	34,100

Table 6

Estimated Quantities of Stone for Breakwaters

With Two Layers of Armor Stone

Harbor	Slope cot θ	Armor Stone tons	Underlayer Stone tons	Core Stone tons	Mattress Stone tons
Caseville	2	20,240	2,820	460	6,400
Harrisville	2	48,600	8,740	2,085	19,600
Leland	2	22,500	6,960	8,315	10,500
Little Lake	2	12,050	1,700	250	5,800
Marquette	2	168,170	62,115	142,295	34,200
Caseville	1.5	18,240	1,960	150	5,410
Harrisville	1.5	43,720	6,320	920	16,440
Leland	1.5	18,850	5,410	4,960	7,540
Little Lake	1.5	10,950	1,190	100	4,880
Marquette	1.5	151,240	52,100	96,246	26,321

Table 7

Stone Cost for One-Layer Armor-Stone Design

Harbor	Armor Stone per ton	Core Stone per ton	Mattress Stone per ton
Caseville	$35	$20	$22
Harrisville	$35	$20	$22
Leland	$35	$20	$22
Little Lake	$40	$20	$22
Marquette	$45	$20	$22

Table 8

Stone Cost for Two-Layer Armor-Stone Design

2H:1V and 1.5H:1V Slopes

Harbor	Armor Stone per ton	Underlayer Stone per ton	Core Stone per ton	Mattress Stone per ton
Caseville	$35	$30	$20	$22
Harrisville	$35	$30	$20	$22
Leland	$35	$30	$20	$22
Little Lake	$35	$30	$20	$22
Marquette	$45	$35	$20	$22

Table 9

Total Estimated Stone Cost for Breakwater Design

Harbor	One-Layer Armor Stone	Two-Layer Armor Stone	
		2H:1V Slope	1.5H:1V Slope
Caseville	$785,200	$1,020,300	$819,200
Harrisville	$1,750,000	$2,238,200	$2,099,900
Leland	$1,181,700	$1,554,000	$1,087,100
Little Lake	$511,800	$618,100	$528,200
Marquette	$10,775,700	$14,133,400	$10,554,700

Table 10

Weight of Stone and Cost per Foot for One-Layer Armor-Stone Breakwater

Harbor	Total Weight tons	Weight/ft tons	Cost/ft dollars
Caseville	29,200	16.4	441
Harrisville	65,300	24.6	658
Leland	44,400	37.0	985
Little Lake	17,200	18.7	555
Marquette	411,000	274.0	7,184

Table 11

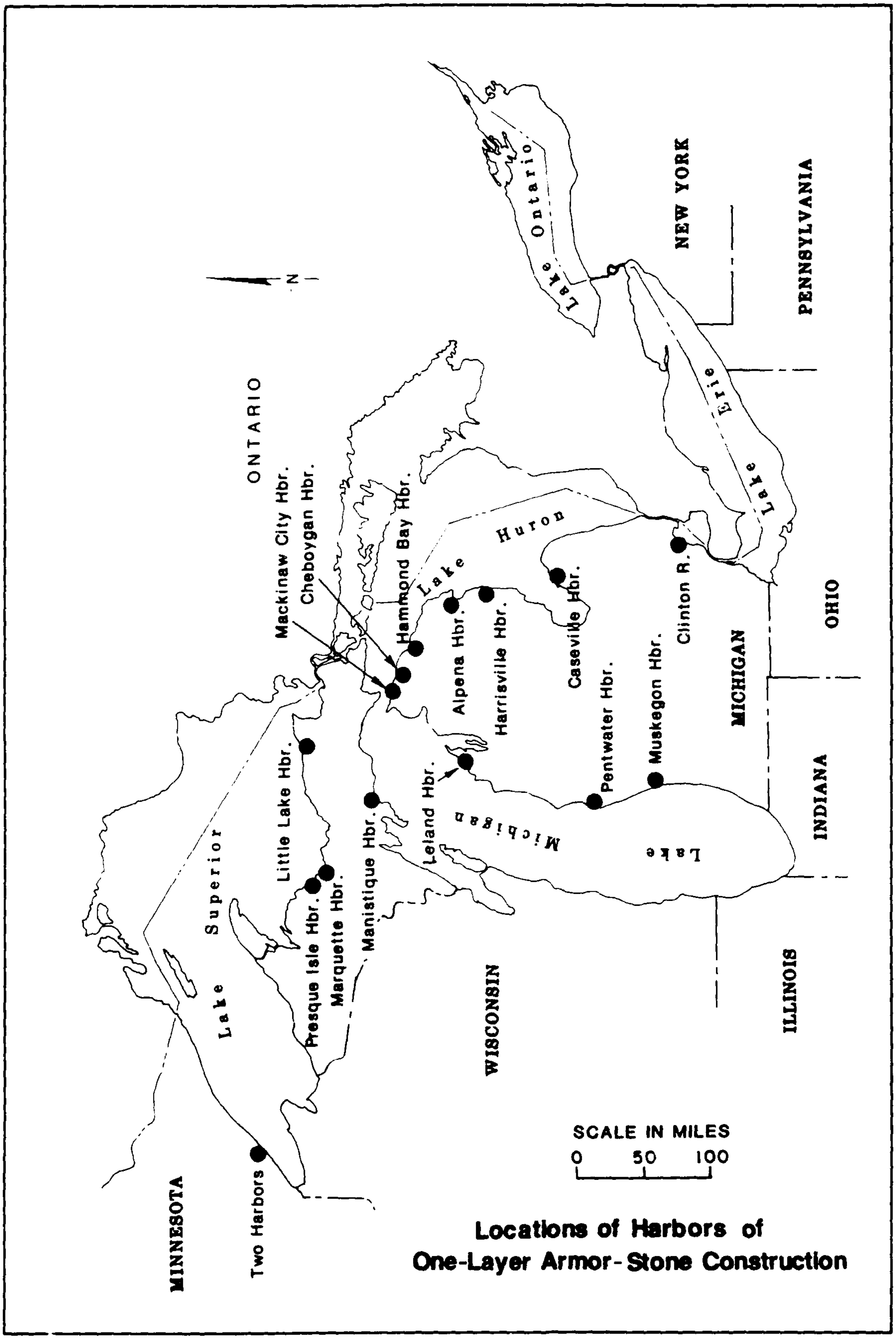
Weight of Stone and Cost per Foot for Two-Layer Armor-Stone Breakwater

Harbor	Breakwater Slope cot θ	Total Weight tons	Weight/ft tons	Cost/ft dollars
Caseville	2	29,920	16.8	573
Harrisville	2	79,025	29.7	842
Leland	2	48,275	40.2	1,295
Little Lake	2	19,800	21.5	670
Marquette	2	406,780	271.2	9,422
Caseville	1.5	25,800	14.5	460
Harrisville	1.5	67,400	25.4	790
Leland	1.5	36,760	30.6	906
Little Lake	1.5	17,120	18.6	573
Marquette	1.5	325,920	217.3	7,036

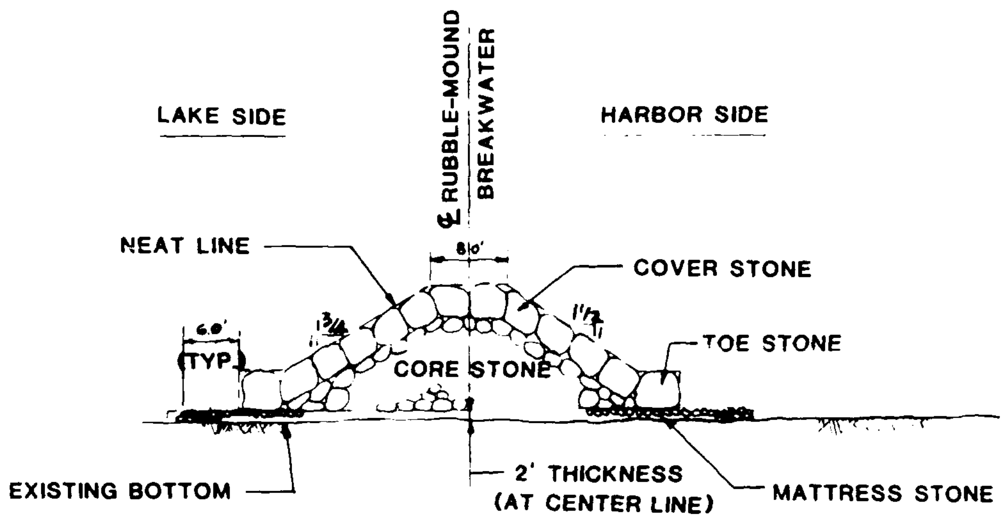
Table 12

Quantity and Size of Stone Required for Repairs to Breakwaters With One Layer of Armor Stone

Harbor	Quantity and Size of Stone Required
Alpena	None
Caseville	None
Cheboygan	Small amount
Clinton River	None
Hammond Bay	2,500 tons, core stone; 107 tons, 0.5- to 2-ton stone
Harrisville	100 tons, +5 ton armor stone
Leland	160 tons, 50- to 300-lb core stone; 100 tons, 0.5- to 3-ton stone; 500 tons, 6- to 12-ton armor stone
Little Lake	Unknown
Mackinaw City	80 tons, 0.5- to 2.0-ton stone
Manistique	None
Marquette	Unknown
Muskegon	2,513 tons, stone size unknown; 1,000 tons, 8- to 12-ton Bedford limestone; 1,020 tons, 3- to 16-ton stone; 510 tons, 1- to 6-ton stone; 412 tons, 0.5- to 3-ton stone; 490 tons, 100- to 500-lb stone
New Buffalo	Unknown
Pentwater	100 tons, 1- to 6-ton stone; 10 tons, 8- to 12-in. stone
Presque Isle	Unknown
Two Harbors	2,000 tons, stone size unknown

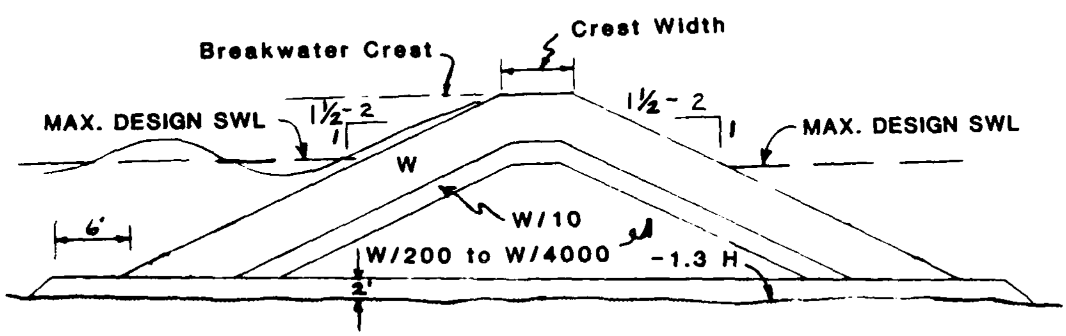


Locations of Harbors of One-Layer Armor-Stone Construction



TYPICAL CROSS SECTION

RUBBLE-MOUND BREAKWATER WITH ONE-LAYER ARMOR STONE



TYPICAL CROSS SECTION

RUBBLE-MOUND BREAKWATER WITH TWO-LAYER ARMOR STONE

APPENDIX A: CASE HISTORIES OF 16 ONE-LAYER ARMOR-STONE BREAKWATERS

<u>Caseville Harbor, Michigan</u>

<u>Existing project</u>

1. The project was authorized by the River and Harbor (R&H) Act of 23 October 1962. The Act provides for dredging an entrance channel 500 ft wide and 10 ft deep to 50 ft wide and 8 ft deep and construction of a rubble-mound breakwater 1,780 ft long on the west side of the entrance channel. The rubble-mound breakwater was completed in 1962 (Figure A1).

<u>Maintenance</u>

2. There have been no repairs.

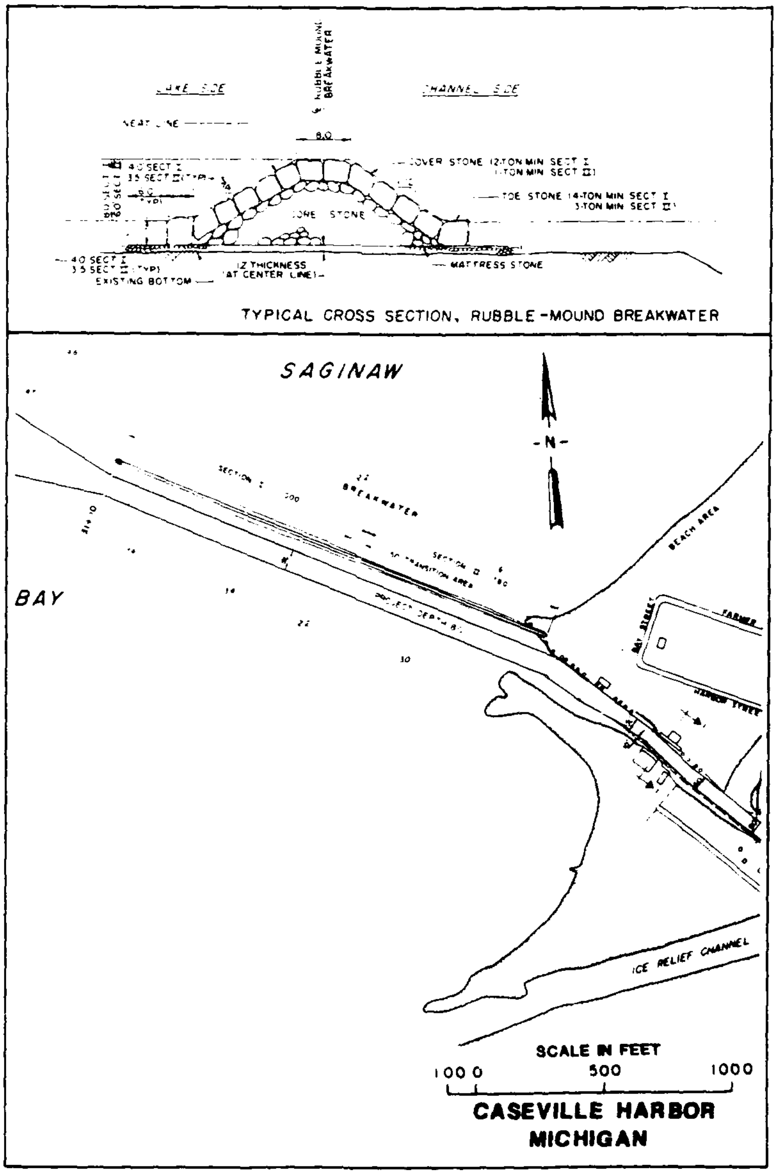


Figure A1. Caseville Harbor, Michigan

Harrisville Harbor, Michigan

Existing project

3. The existing project was authorized by the R&H Act of 2 March 1945. The project provides for a harbor of refuge dredged to a 10-ft depth, protected by rubble-mound breakwaters, and a 10-ft-deep harbor entrance channel extending to the 12-ft contour in Lake Huron. The project was completed in 1959 (Figure A2).

Maintenance

4. The outer end of the main breakwater and the entrance light were repaired in 1971. One hundred tons of armor stone +5 tons were placed. The outer end of the main breakwater and the entrance light were repaired again in 1974.

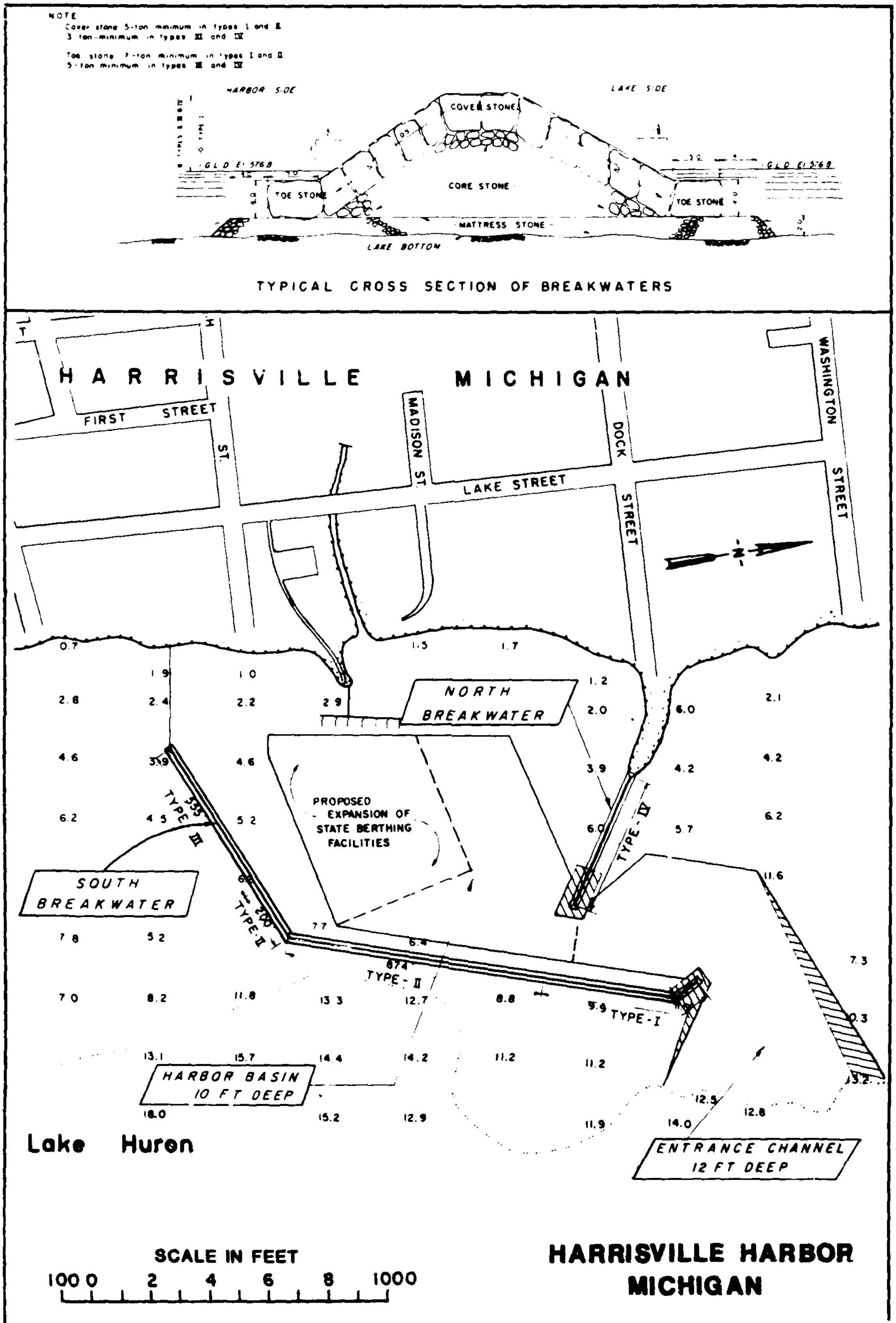


Figure A2. Harrisville Harbor, Michigan

Leland Harbor, Michigan

Existing project

5. The project was authorized by the R&H Acts of 30 August 1935 and 23 October 1962. The Acts provided for a harbor of refuge comprised of a rubble-mound breakwater about 1,200 ft long, a protected anchorage and maneuvering area about 3 acres in extent and 10 ft deep, a 12-ft-deep flared approach channel decreasing in width to 90 ft; an existing 440-ft-long south pier, a 40-ft-wide, 6-ft-deep channel extending from the southeast corner of the anchorage area to the mouth of the Carp River; and elimination of the existing north pier. The rubble-mound breakwater was completed in 1968 (Figure A3).

Maintenance

6. In 1983, areas of stone slippage, settlement, and washout of core and cover stone were repaired by removing existing cover stone, placing new core stone, and replacing cover stone, or, where needed, adding new cover stone. Areas of large voids or gaps were filled by placement of core and small riprap stone. One hundred sixty tons of 50- to 300-lb core stone, 100 tons of 0.5- to 3-ton stone, and 500 tons of 6- to 12-ton armor stone were used.

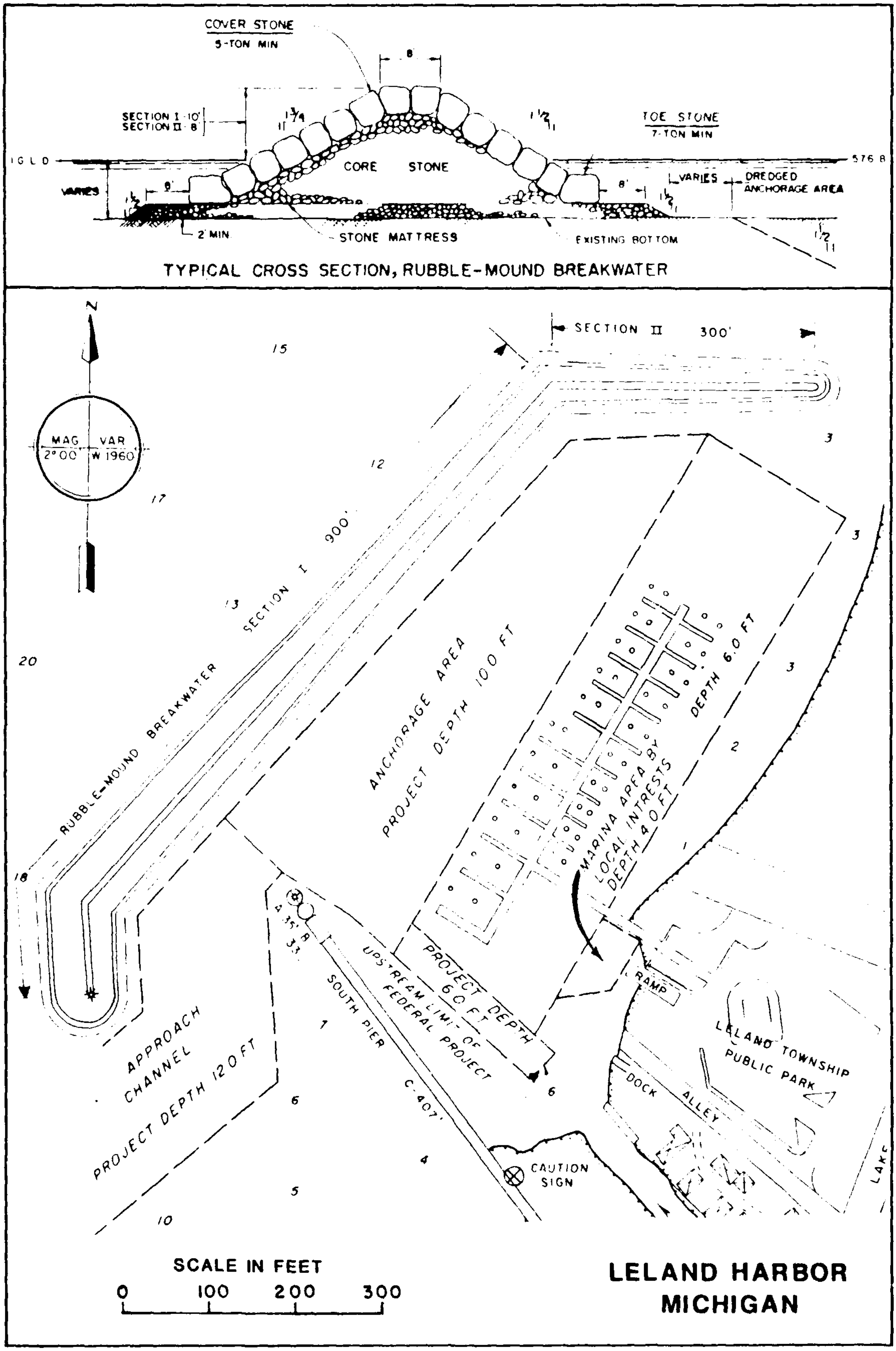


Figure A3. Leland Harbor, Michigan

Little Lake Harbor, Michigan

Existing project

7. The project was authorized by the R&H Act of 2 March 1945. The project provides for a small craft harbor of refuge by dredging an entrance channel 12 ft deep from Lake Superior into Little Lake, protected by two rubble-mound breakwaters, on the east and west, the lengths of which are 360 and 1,135 ft, respectively. The project was completed in 1964 (Figure A4).

Maintenance

8. In 1964, there was a report of a large amount of settlement at the outer end of the rubble-mound section of the west breakwater. The outer section, 130 to 140 ft long, settled up to a maximum of approximately 5 ft. Considerable lakeward displacement of cover stone was observed. There was little evidence of any movement of cover stone toward the harbor. Inspection reports of the core stone indicated only small stone from 5 to 50 or 100 lb were sighted in some problem areas. The breakwater was repaired in 1964.

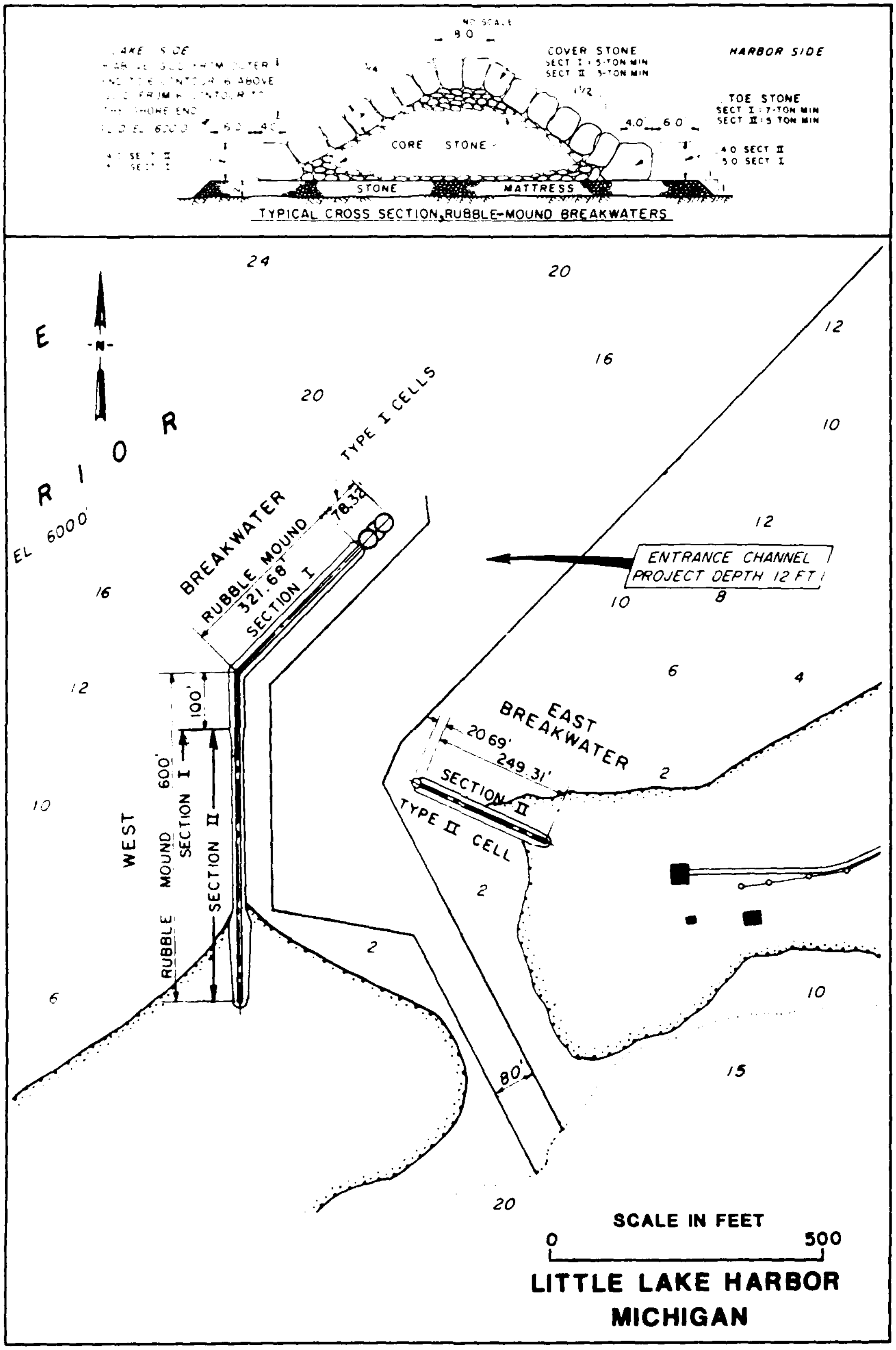


Figure A4. Little Lake Harbor, Michigan

Marquette Harbor, Michigan

Existing project

9. The existing project was authorized under the R&H Acts of 2 March 1867, 11 August 1888, 25 June 1910, 30 August 1955, and 14 July 1960. The project provides for 4,510 ft of breakwater; the inner 3,010 ft will be timber and concrete and the remaining 1,500 ft will be rubble mound. The project also provides for dredging a harbor basin 1,600 by 3,600 ft to a depth of 27 ft. The original project was completed in 1935. Deepening of the harbor under the 1960 Act was completed in September 1966. The rubble-mound breakwater was completed in 1918 (Figure A5).

Maintenance

10. The rubble-mound breakwater has required some maintenance which was completed by hired labor. The rubble-mound breakwater did not require rehabilitation in 1965 when the concrete portion of the breakwater was rehabilitated under contract. The armor stones are boulders which were dredged from the lake. The estimated weight of the armor stones is 15 to 25 tons.

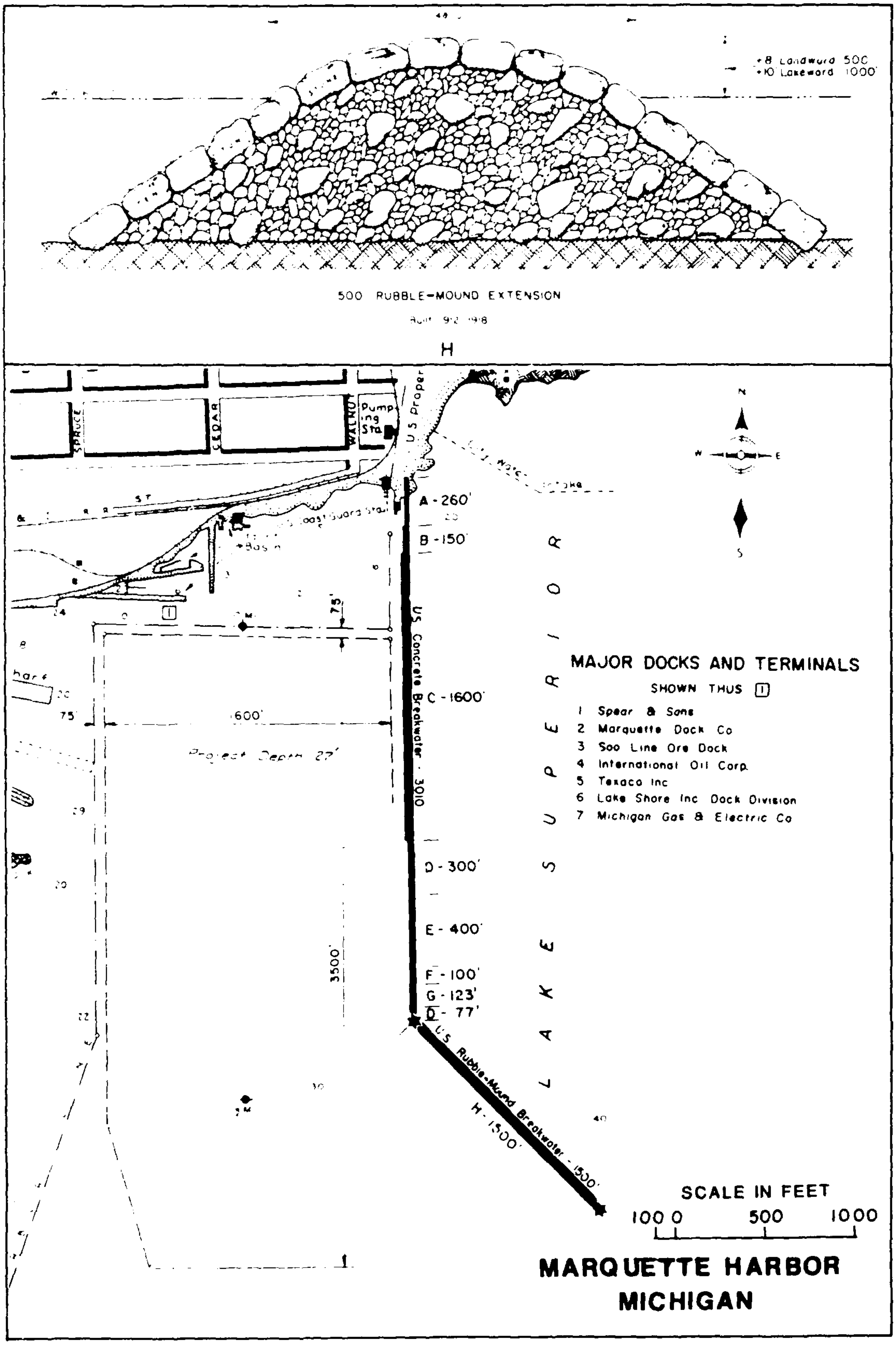


Figure A5. Marquette Harbor, Michigan

Alpena Harbor, Michigan

Existing project

11. The existing project was adopted by the R&H Acts of 19 September 1890, 2 March 1919, 22 September 1922, 30 August 1935, and 27 October 1965. These Acts provide for a channel from 24 ft deep with a width of 200 ft to 18.5 ft deep with a width of 75 ft. The channel entrance is protected by a 700-ft-long rubble-mound breakwater located on the south side of the channel. The present harbor was completed in 1939 (Figure A6).

Maintenance

12. There have been no repairs.

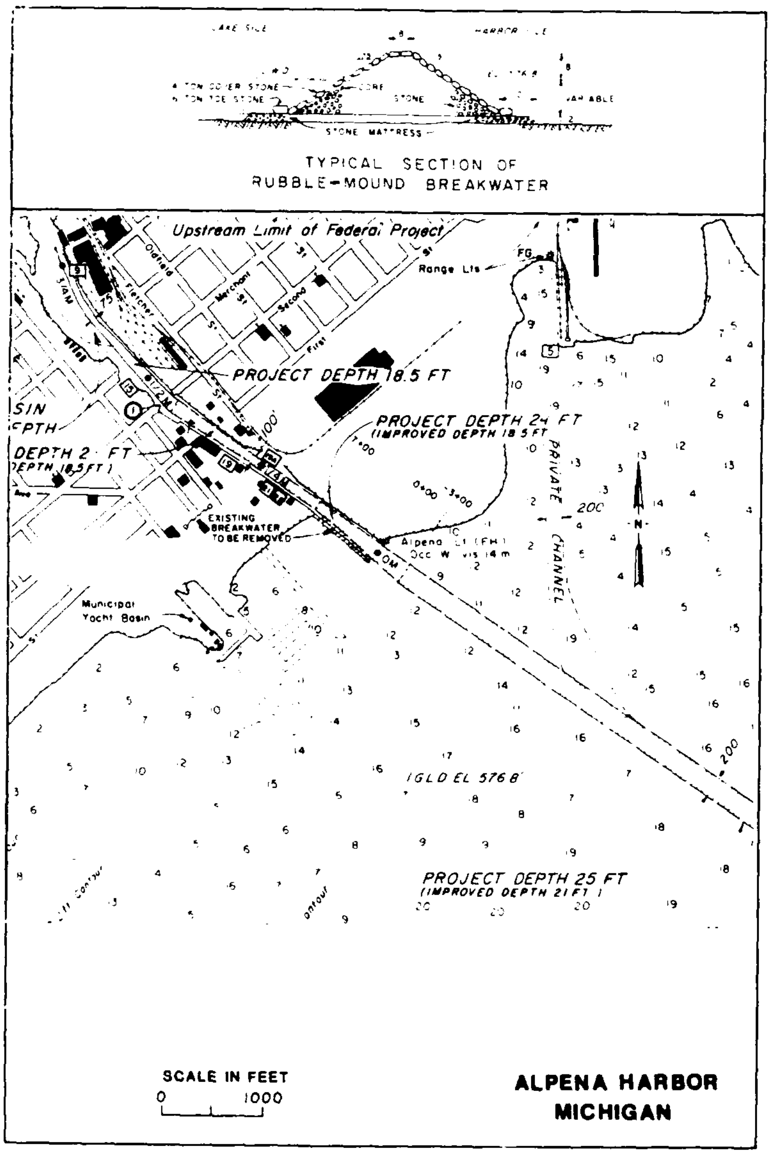


Figure A6. Alpena Harbor, Michigan

Existing project

13. The existing project was authorized by the R&H Acts of 3 June 1896, 2 March 1907, 26 August 1937, and 17 May 1950. These Acts provide for a channel 21 ft deep and 200 ft wide to 18.5 ft deep and 60 ft wide. The channel was completed in 1950. The project was modified under provisions of Section 107 of the 1960 River and Harbor Act, Public Law 88645, by Headquarters, US Army Corps of Engineers (HQUSACE) on 21 October 1964 to provide for the construction of a rubble-mound breakwater approximately 775 ft long on the site of the existing west pier at the mouth of the river. The rubble-mound breakwater was completed in 1969 (Figure A7).

Maintenance

14. There have been no repairs.

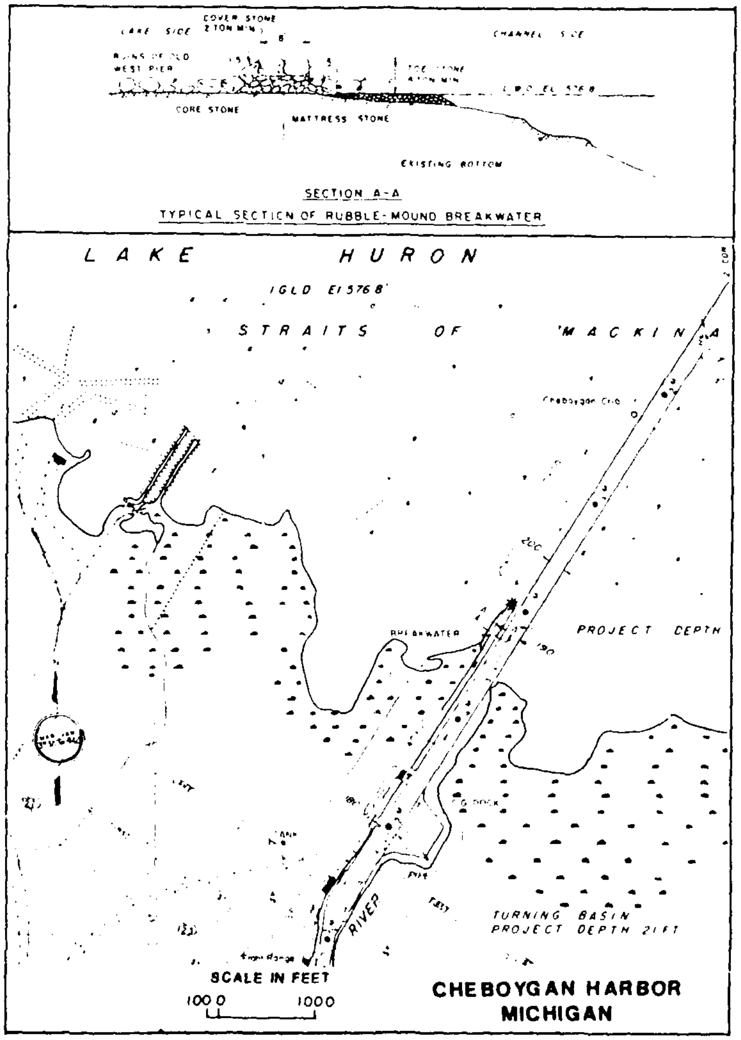


Figure A7. Cheboygan Harbor, Michigan

Existing project

15. The existing project was adopted by the R&H Act of 5 August 1886 and modified under the provision of Section 107 of the R&H Act of 1960. The project provides for an entrance channel from 300 ft wide and 8 ft deep to 50 ft wide and 8 ft deep. The entrance channel is protected by a rubble-mound breakwater on the north side and an earth-fill breakwater on the south side of the channel. The project was completed in 1966.

Maintenance

16. There has been no repairs.

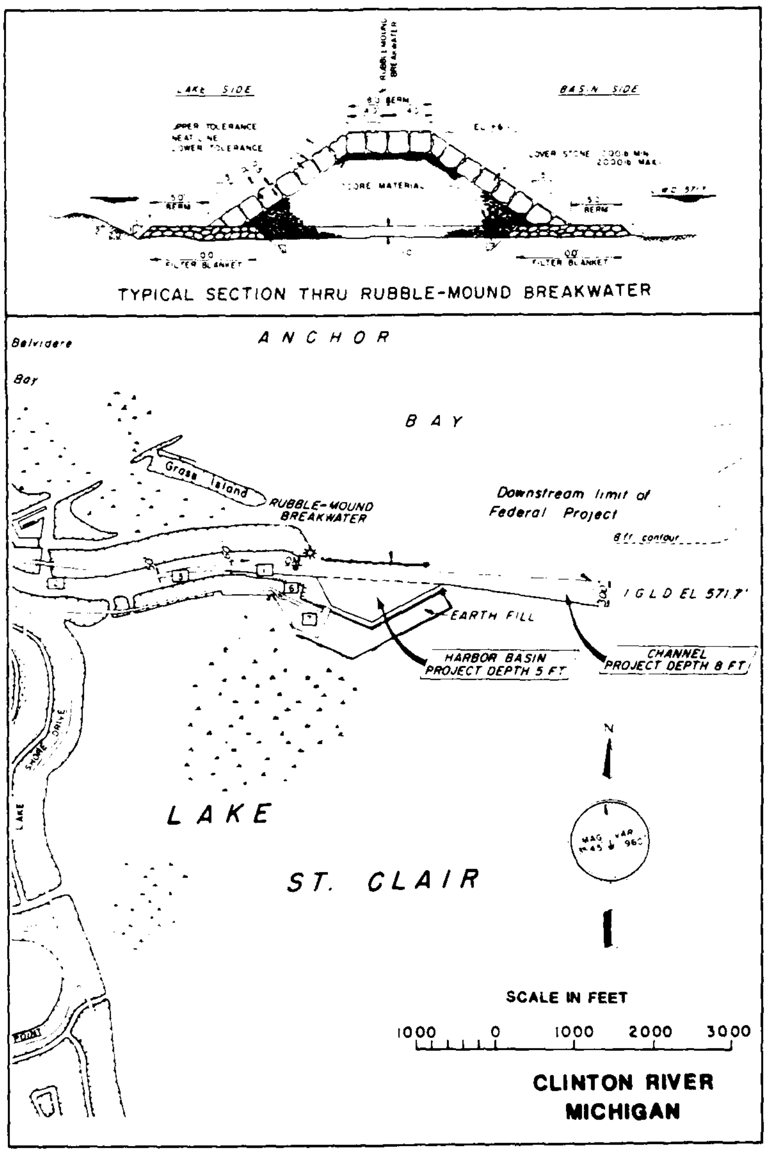


Figure A8. Clinton River, Michigan

Hammond Bay Harbor, Michigan

Existing project

17. The existing project was adopted by the R&H Act of 2 March 1945. The Act provides for a harbor of refuge protected by breakwater structures extending to the 12-ft contour in Hammond Bay and for dredging a harbor basin to a depth of 10 ft. The project was completed in 1965 (Figure A9).

Maintenance

18. The north end of the main breakwater was rehabilitated in August of 1982. Twenty-five hundred tons of core stone were added. The armor stone was reused. The north end of the main breakwater was repaired in the same area in August of 1985. One hundred seven tons of 0.5- to 2-ton stone was placed on the lakeside. Armor stone was recovered and replaced.

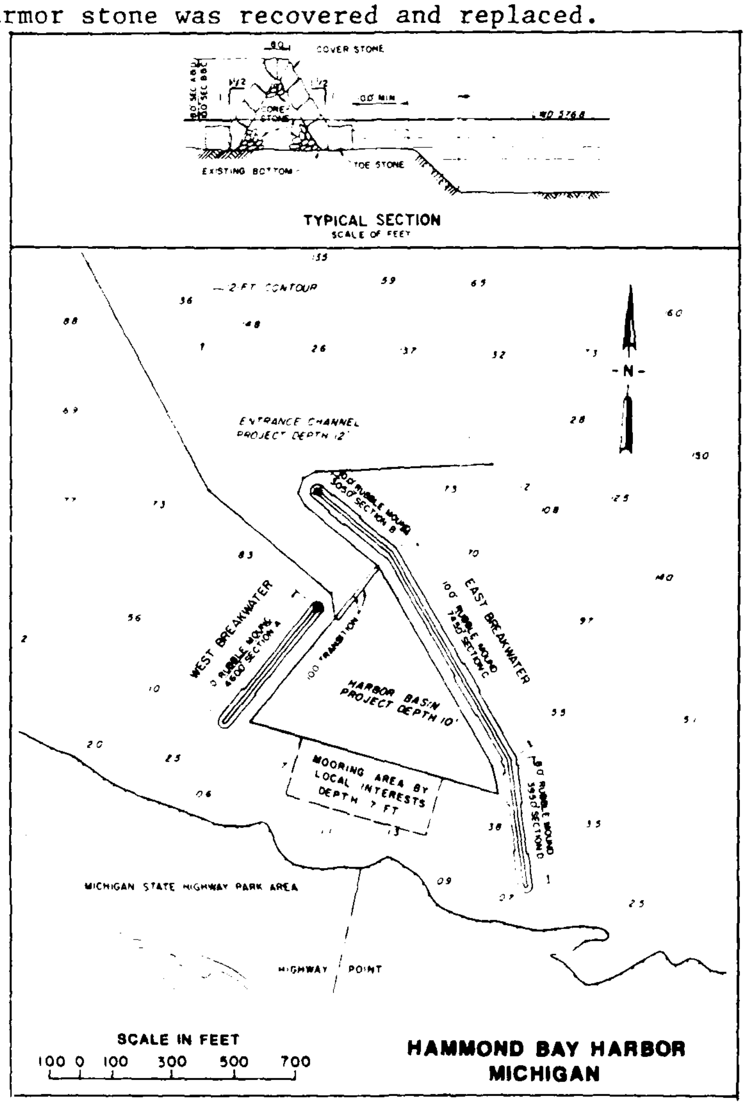


Figure A9. Hammond Bay Harbor, Michigan

Mackinaw City Harbor, Michigan

Existing project

19. The existing project was authorized by HQUSACE on 15 January 1965 pursuant to Section 107 of the 1960 R&H Act, Public Law 86-645. This project provides for a breakwater about 430 ft long, a channel 100 ft wide with a depth of 10 ft, and a protected area of approximately 3.3 acres from 6 to 8 ft in depth. The rubble-mound breakwater was completed in 1965 (Figure A10).

Maintenance

20. In August of 1985, the outer end of the breakwater was repaired. Eighty tons of new stone from 0.5 to 2 tons were added. An undetermined quantity of old stone was recovered and replaced.

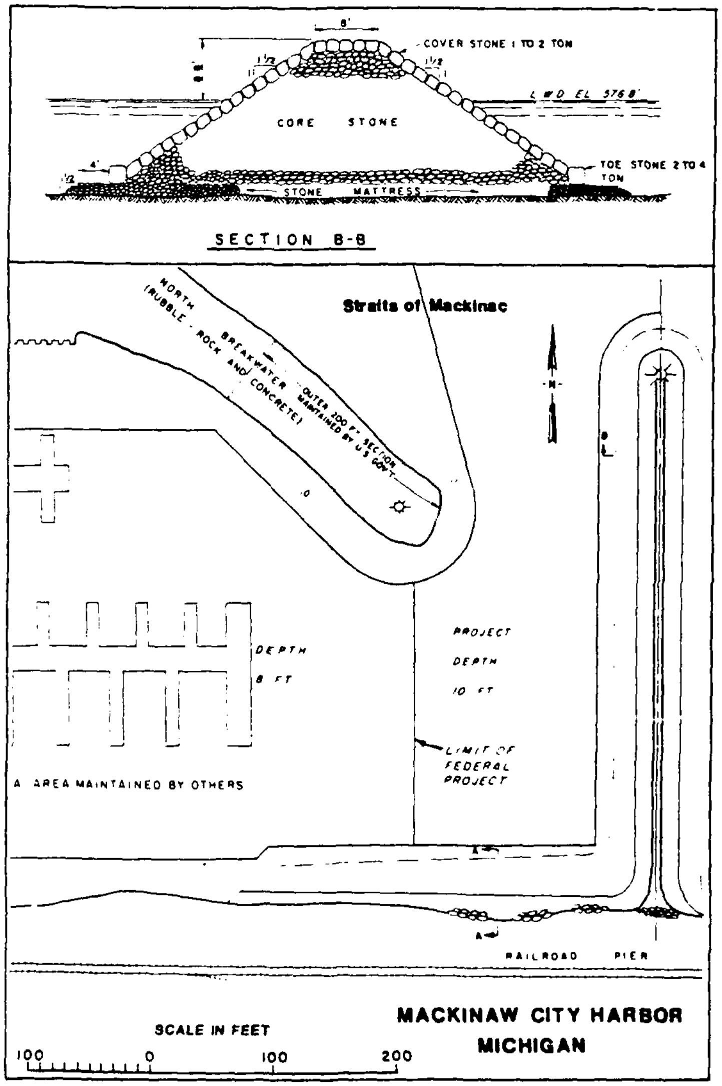


Figure A10. Mackinaw City Harbor, Michigan

Manistique Harbor, Michigan

Existing project

21. The existing project was authorized by the R&H Acts of 3 March 1905, 2 March 1907, and 17 May 1950. The project provides for two breakwaters extending from the shore on either side of the mouth of the Manistique River, 1,744 and 1,480 ft in length for the east and west breakwaters, respectively, and for a pier of 375 ft long on the west side of the river mouth. The project further provides for an entrance channel 19 ft deep from that depth in the lake to a point about 300 ft landward of the harbor entrance, thence 18 ft to a point 1,150 ft upstream from the mouth of the river, and thence 18 ft, except where rock is encountered at less depth, for a further distance of 500 ft, with widths of 246 ft at the breakwater entrance, increasing to 475 ft through the outer basin, decreasing to 215 ft at the river mouth, thence varying from 180 ft at the upper limit. The total length of the channel is 4,100 ft. The project was completed in 1961. The rubble-mound breakwater sections were completed in 1953 and 1963 (Figure A11).

Maintenance

22. There have been no repairs made.

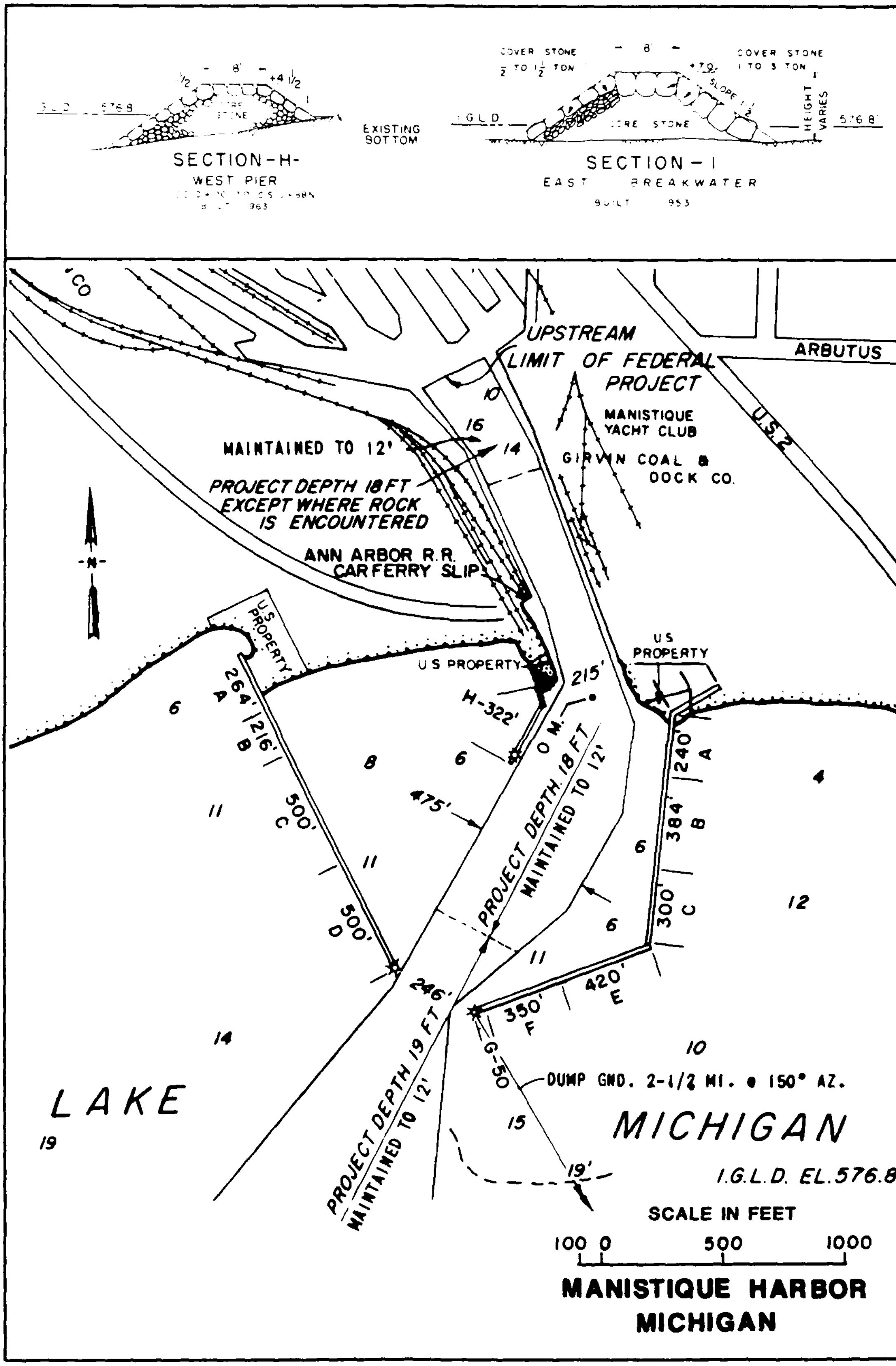


Figure A11. Manistique Harbor, Michigan

Muskegon Harbor, Michigan

Existing project

23. The existing project was adopted by the R&H Acts of 13 June 1902, 3 March 1935, 30 August 1935, and 23 October 1962. The project provides for an exterior basin in Lake Michigan formed by two arrowhead breakwaters, the south 1,514 ft long and the north 1,404 ft long, 500 ft apart at the outer ends, diverting at an angle of about 90 deg, the inner ends connected with the shore by suitable structures, 1,660 and 1,561 ft long on the north and south sides, respectively; for repairing and maintaining the revetment around the old car ferry slip on the south side of the entrance channel; and for dredging a flared entrance channel with a depth of 29 ft from deep water in Lake Michigan and a width of 380 ft at the entrance to a depth of 27 ft over a width of 200 ft in the channel between the inner piers to Muskegon Lake. The existing project was completed in 1956. The rubble-mound breakwater was completed in 1930 (Figure A12).

Maintenance

24. In 1975, 2,513 tons of stone were placed on the north breakwater. In 1980, 1,000 tons of 8- to 12-ton Bedford Limestone armor stones were placed around the west end of the north breakwater. In 1981, 510 tons of 1- to 6-ton stone and 490 tons of 100- to 500-lb fill stone were placed on the north breakwater. In 1982, 1,020 tons of 3- to 16-ton stone were placed around the west end of the north breakwater. Three hundred twelve tons of 0.5- to 3-ton stone were placed in voids and gaps 300 ft east of the navigation light. In 1983, 1,000 tons of 0.5- to 3-ton stone were placed in large voids and gaps of the north breakwater.

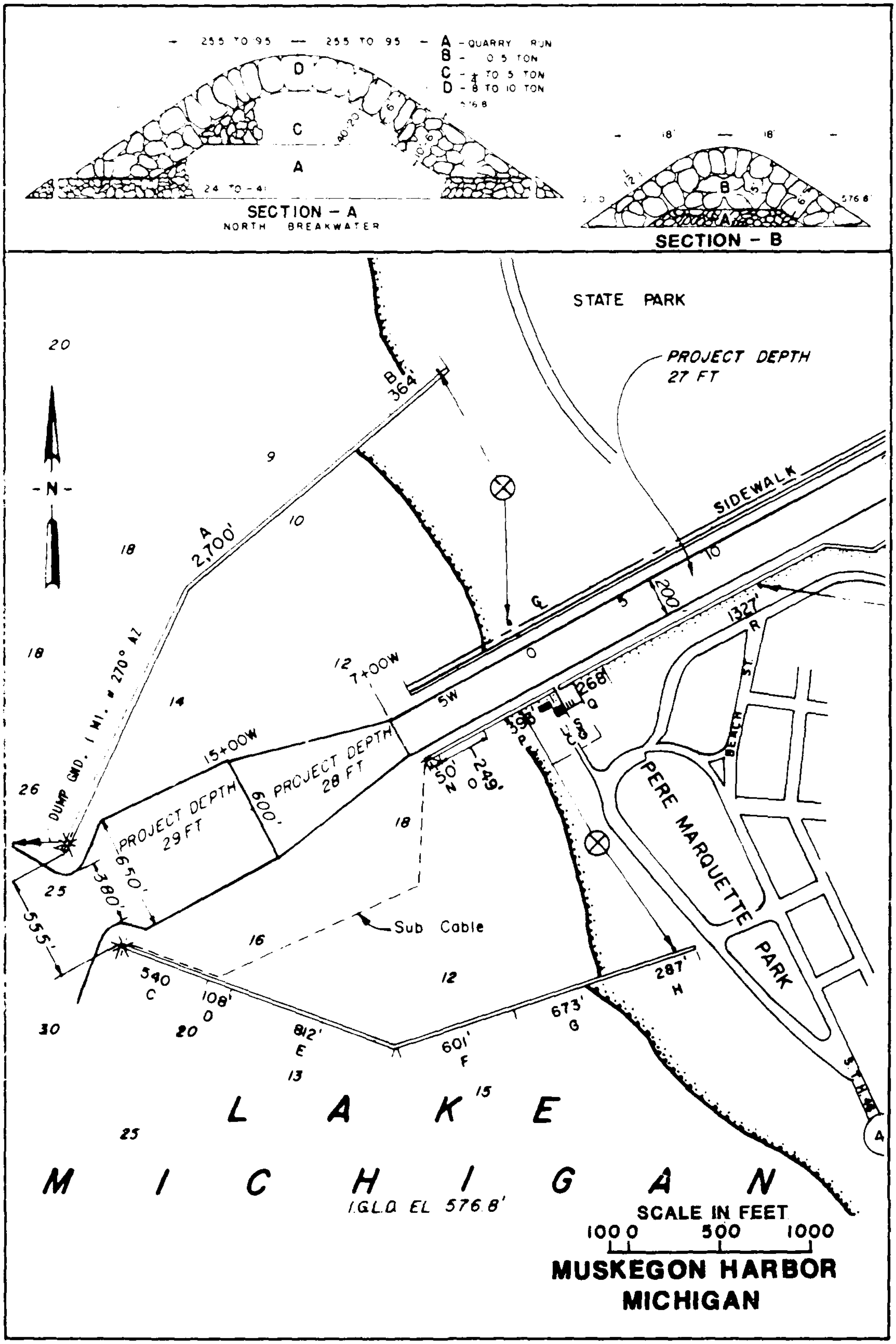


Figure A12. Muskegon Harbor, Michigan

New Buffalo Harbor, Michigan

Existing project

25. The existing project was authorized by the R&H Act of 1962. The project includes construction of two breakwaters, one extending lakeward for 1,305 ft from the shore northeast of the Galien River mouth, and the other breakwater extending 740 ft from the shore on the southwest side; and dredging a channel 10 ft deep, 80 to 180 ft wide, and about 850 ft long from the lake to the river mouth, thence 8 ft deep and 80 ft wide for 1,250 ft in the river. The project was completed in 1975 (Figure A13).

Maintenance

26. The north and south breakwaters were repaired in 1983. The north breakwater head required 150 tons of 6- to 12-ton armor stone and 20 tons of 50- to 300-lb core stone. There were 385 tons of 6- to 12-ton armor stone and 20 tons of 50- to 300-lb core stone placed on the balance of the north breakwater. The south breakwater required 75 tons of 6- to 12-ton stone.

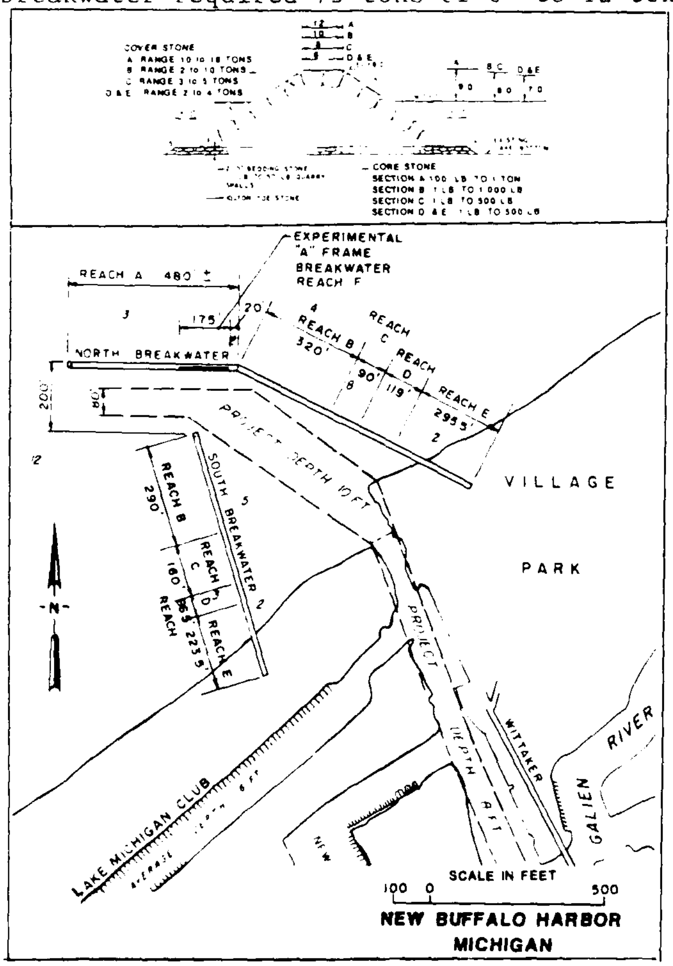


Figure A13. New Buffalo Harbor, Michigan

Pentwater Harbor, Michigan

Existing project

27. The existing project was authorized by the R&H Acts of 2 March 1867, 3 March 1873, 5 July 1884, 13 July 1892, and 2 March 1907. These Acts provide for widening the old entrance channel to 150 ft between parallel piers and revetments with the channel extending from Lake Michigan to Pentwater Lake with a depth of 16 ft. The piers and revetments were built of stone-filled timber cribs and piling and were provided with concrete superstructures. The north pier and revetment were completed in 1885 with a length of 1,847 ft. The present length of the north pier and revetment is 2,022 ft; 204 ft of deteriorated pier was removed in 1932. In 1960, the north pier was extended 60 ft by construction of a rubble-mound structure. The existing project was completed in 1959 except for the 200-ft extension to the south pier which is not considered necessary under present conditions. It has also been determined that an 80-ft channel between Lake Michigan and Pentwater Lake is adequate for the commerce involved, and the project is presently being maintained to this width. The channel is presently being maintained to a depth of 12 ft. The rubble-mound breakwater section was completed in 1959 (Figure A14).

Maintenance

28. In 1981, 100 tons of 1- to 6-ton stone were placed along or in the rubble-mound structure. In 1982, 10 tons of 8- to 12-in. stone were placed in gaps between cover stones of the rubble mound.

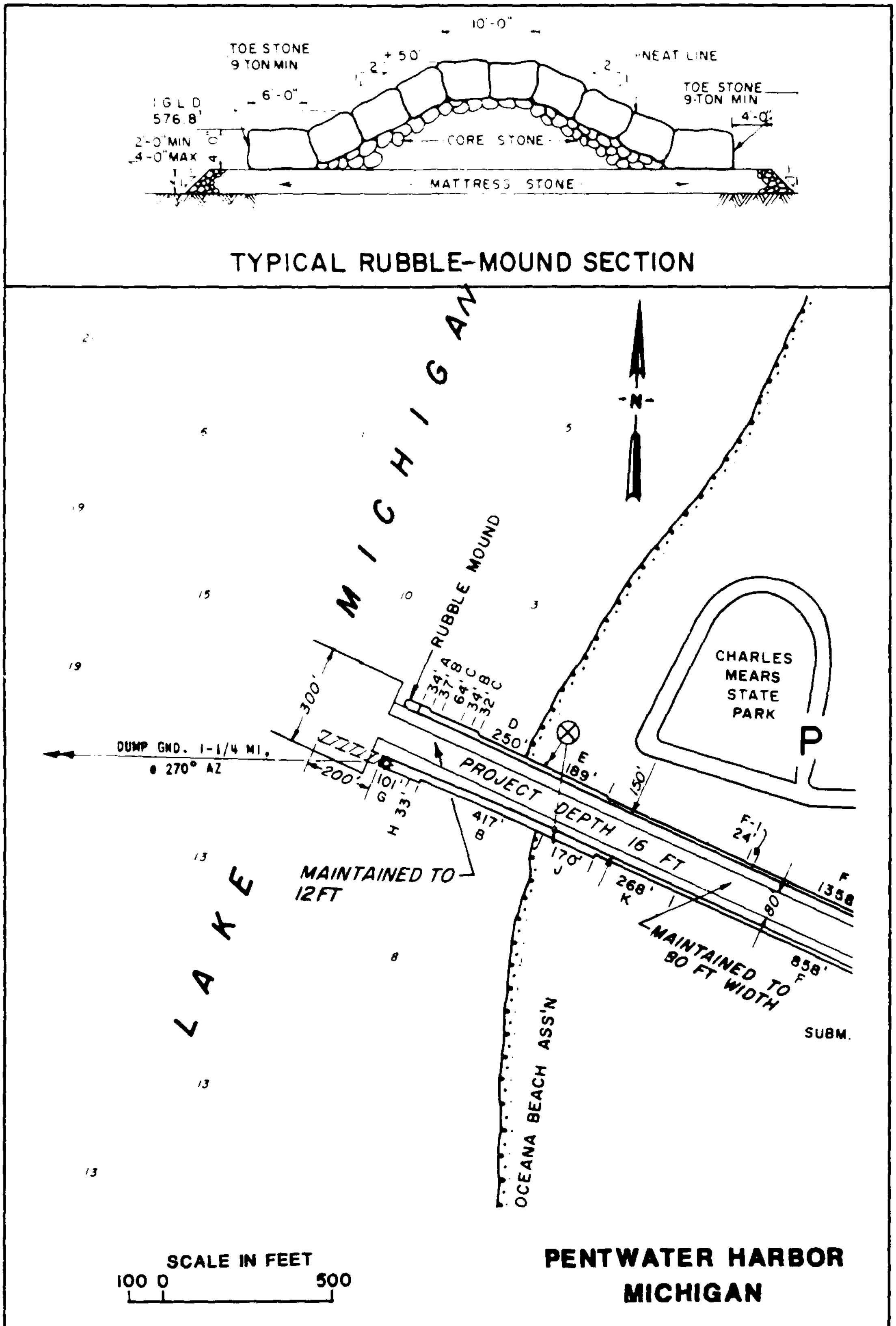


Figure A14. Pentwater Harbor, Michigan

Presque Isle Harbor, Michigan

Existing project

29. The existing project was authorized by the R&H Acts of 3 June 1896, 13 June 1902, 30 August 1935, and 14 July 1960. These Acts provide for a breakwater 2,816 ft long off Presque Island and the dredging of a maneuvering area of irregular shape, the inner basin of which is 28 ft deep and the approach 30 ft deep. The project was completed in 1939 (Figure A15).

Maintenance

30. There has been minor repair work. The breakwater has very heavy armor stone which was quarried from hard rock. The estimated weight of the armor stone is up to 30 tons.

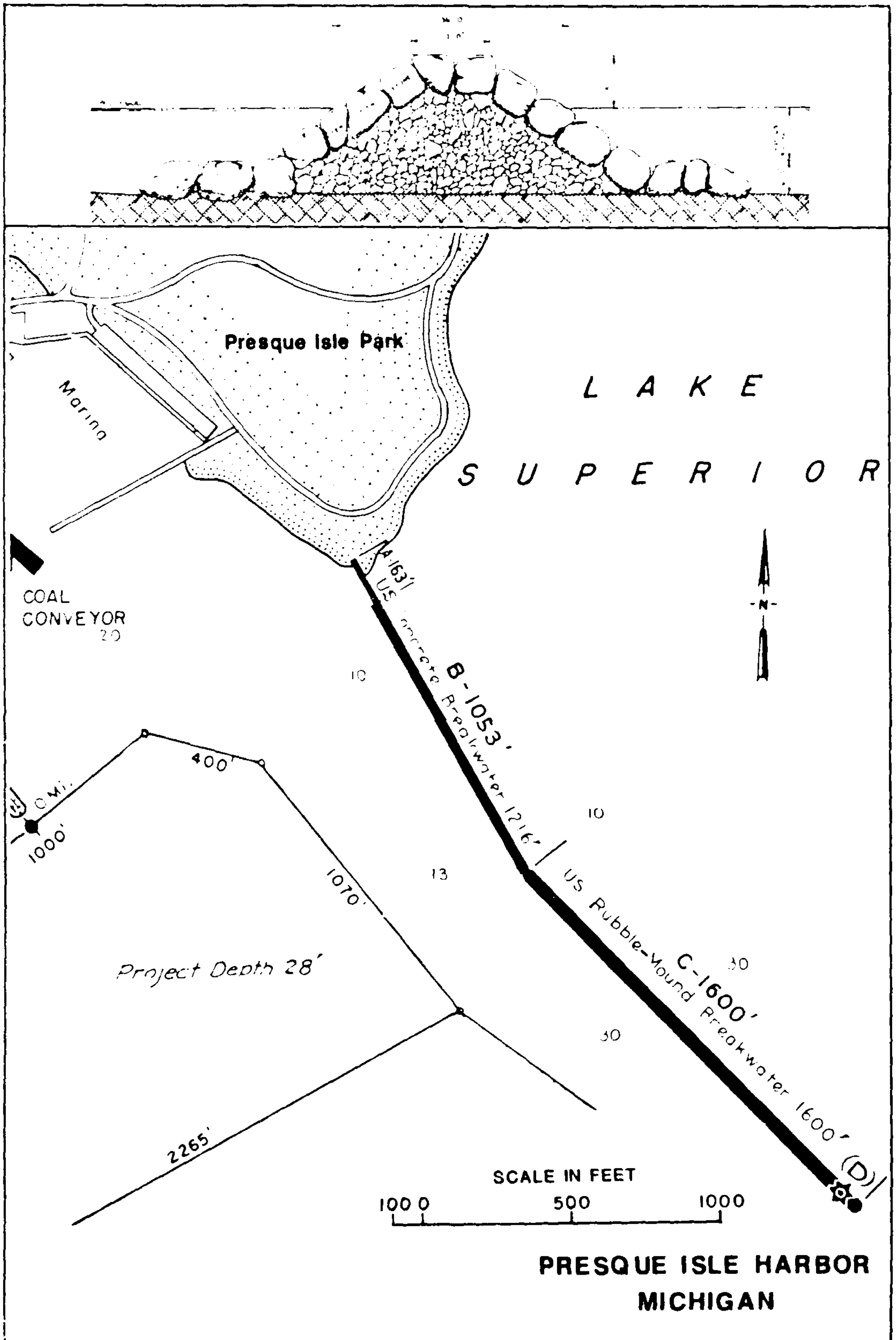


Figure A15. Presque Isle Harbor, Michigan

Two Harbors, Minnesota

Existing project

31. The existing project was authorized by the R&H Act of 5 August 1886 and followed by subsequent authorizations of 30 August 1935, 7 November 1945, and 14 July 1960. The harbor calls for narrowing the natural entrance by construction of two breakwaters, 1,628 and 900 ft long, from eastern and western points of the bay, respectively. It also provides for dredging a maneuvering area on the north side of the harbor to 28 and 30 ft deep. A walkway on the east breakwater is provided for public recreational use. The existing project was completed in 1980. The rubble-mound breakwater was completed in 1948 (Figure A16).

Maintenance

32. Approximately 2,000 tons of rock were placed on the lake and harbor sides of the breakwater in August and September of 1962. No other repair work has been done.

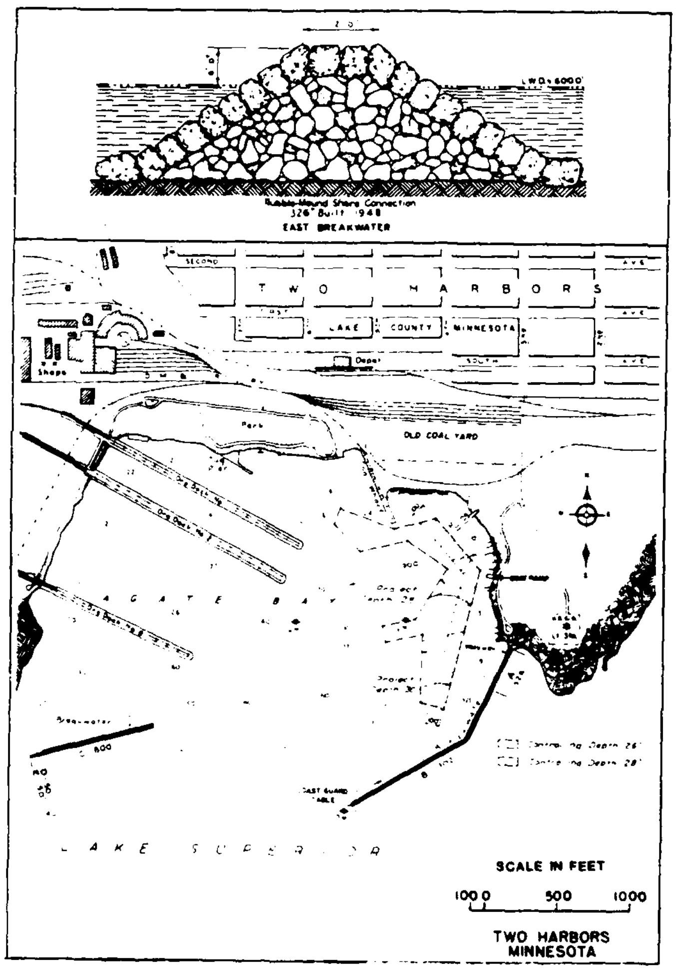


Figure A16. Two Harbors, Minnesota

APPENDIX B: NOTATION

NOTATION

B	Rubble structure crest width, feet
H	Design wave height
KD	Armor unit stability coefficient
r	Armor-layer thickness
W	Weight of individual armor unit in primary cover layer; weight of individual units, any layer
w_r	Unit weight of armor (rock) unit (saturated surface dry)
θ	Theta, angle of structure face relative to horizontal